Weather and Climate Extremes 4 (2014) 96–108

Contents lists available at ScienceDirect

Weather and Climate Extremes

journal homepage: www.elsevier.com/locate/wace

Quantifying the impact of weather extremes on global food security: A spatial bio-economic approach

Sika Gbegbelegbe [a,*], Uran Chung [b], Bekele Shiferaw [a], Siwa Msangi [c], Kindie Tesfaye [d]

[a] International Maize and Wheat Improvement Center (CIMMYT), Kenya Office, PO Box 1041, Village Market, Nairobi, Kenya
[b] International Maize and Wheat Improvement Center (CIMMYT), Apdo. Postal 6-641, CP 06600 Mexico DF, Mexico
[c] International Food Policy Research Institute (IFPRI), Washington, DC, USA
[d] International Maize and Wheat Improvement Center (CIMMYT), Ethiopia Office, PO Box 5689, Addis Ababa, Ethiopia

ARTICLE INFO

Article history:
Received 28 November 2013
Received in revised form
10 May 2014
Accepted 22 May 2014
Available online 12 June 2014

Keywords:
Spatial bio-economic modelling
Weather extreme
IMPACT
Food security
Developing world

ABSTRACT

This study uses a spatial bio-economic modelling framework to estimate the impact of the 2012 weather extreme in the USA on food security in the developing world. The study also quantifies the potential effects of a similar weather extreme occurring in 2050 under climate change. The study results indicate that weather extremes that affect maize productivity in key grain baskets can negatively affect food security in vulnerable countries. The 2012 weather extreme which occurred in the USA reduced US and global maize production by 29% compared to trend; maize consumption in the country decreased by 5% only and this resulted in less surplus maize for exports from the largest maize exporter in the world. Global maize production decreased by 6% compared to trend. The decrease in global maize production coupled with a reduction in the volume of global maize exports worsened food insecurity in eastern Africa, the Caribbean and Central America and India. The effects of the weather extreme on global food security would be worse, if the latter were to occur under climate change in 2050, assuming no climate change adaptation worldwide over the years. In addition, the hardest-hit regions would remain the same, whether the weather extreme occurs in 2012 instead of 2050: Sub-Saharan Africa (SSA), South Asia and the Latin America and Caribbean (LAC) region. However, sustained growth in per capita income across world economies between 2000 and 2050 would allow few countries in SSA and the LAC region to virtually eliminate hunger within their borders. In these countries, per capita income would be high enough by 2050 to completely offset the negative effect of the weather extreme. The study results are also consistent with USDA's estimates on US and global maize production and consumption in 2012 after the weather extreme. Some discrepancy is found on the volume of global maize trade; this implies that the bio-economic model likely overestimates the effect of the weather extreme on food insecurity. However, the trends from the analysis are likely to be valid. Further research would involve using a CGE model that can capture the net effects of weather extremes.

1. Introduction

The world food system is more vulnerable to weather extremes for various reasons, the key one being that crop yield changes have not been keeping up with rising food demand worldwide (Ortiz et al., 2008; Boyer et al., 2013). Yield growth rates have collapsed or are stagnating in about 30%, 38% and 39% of global harvested area for maize, rice and wheat, respectively (Ray et al., 2012). In addition, wheat yield gains across the developing world have remained below population growth in recent years (Ortiz et al., 2008). Other factors that make the global food system more vulnerable to weather extremes include the globalization of grain markets and rising fuel prices which increase food transportation costs (Brown and Funk, 2008).

The globalization of grain markets implies that weather extremes that reduce food harvests in key breadbaskets influence world food prices and can have negative effects on food security in poor net maize-importing countries (Chung et al., submitted for publication). However, there is no empirical study on the subject. Most studies that aim to estimate the socio-economic impact of climate extremes use statistical approaches to quantify the direct economic losses brought by climate extremes (Pielke and Landsea, 1998; Changnon, 2003a; Hallegatte, 2007; Pielke, 2007). Such direct losses usually consist of estimated financial losses (e.g. property or crop losses) closely linked to the climate extreme (Changnon, 2003a; Changnon, 2003b; Hallegatte, 2007; Hallegatte et al., 2007). Other studies have attempted to quantify the effect of climate extremes on human mortality (Kunkel et al., 1999;

* Corresponding author. Tel.: +254 20 722 4630, mobile: +254 71 148 9232.
E-mail address: g.sika@cgiar.org (S. Gbegbelegbe).

http://dx.doi.org/10.1016/j.wace.2014.05.005

Deschenes and Moretti, 2007). Studies that have estimated the primary and secondary effects of climate extremes used process-based models to analyse the impact of extreme weather events on poverty vulnerability in developing countries (Adger, 1999; Ahmed et al., 2009), producer and consumer welfare in Spain (Mechler et al., 2010), and food security in China (Nelson et al., 2010). Unlike statistical models, process-based models have the ability to consider trade effects in the socio-economic analysis of climate extremes.

Mechler et al. (2010) used a process-based model, to quantify the economic effect of a combined heat wave and drought in Spain. Similarly, Nelson et al. (2010) used a process-based model to estimate the impact of an extended drought in China on food security in the nation. These two studies highlighted the need to consider trade effects in the economic analysis of extreme events. Since the USA is the leading maize producer and exporter globally, it is very likely that the extreme weather event of 2012 in the USA would have indirect secondary effects on food security in other parts of the world where maize is a staple food.

This study assesses the impact of the 2012 weather extreme in the USA on food security across the developing world. The study also estimates the plausible effects on food security of a similar weather extreme occurring in 2050.

2. Materials and methods

2.1. Methodological framework: spatial bio-economic modelling

A spatial bio-economic framework which is described in Nelson et al. (2010) and illustrated in Fig. 1 was used to estimate the global impact of the climate extreme occurring in the USA. Crop and spatial modelling were combined to estimate the biophysical impact of the climate extreme on maize yields in the USA under various climate models. The analysis involves a high performance computing cluster where the Geographic Resources Analysis Support System (GRASS, http://grass.osgeo.org/) is used to handle spatial data defined and the Decision Support System for Agrotechnology Transfer (DSSAT) (Hoogenboom et al., 1999; Jones et al., 2003) was used to simulate crop yield and other biophysical variables. The biophysical results were defined at the 5′ spatial resolution were averaged to the level of Food Production Units (FPUs), which are production zones defined within countries (Rosegrant and et al., 2012). These results were then inputted into the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) to derive socio-economic results. IMPACT is a multi-market, multi-country model that focuses on the agricultural sector and projects trends in national and global food security under alternative scenarios on population growth, income growth and future climates (Rosegrant et al., 2008; Rosegrant and et al., 2012).

2.2. Incorporation of biophysical results into IMPACT

Chung et al. (submitted for publication) used geo-spatial crop modelling at the 5′ spatial resolution to estimate the impact of the weather extreme on maize yields across the USA. The biophysical results were then aggregated to the levels of Food Production Units and inputted into IMPACT. More specifically, the biophysical maize yield change brought by the extreme weather event is used as maize area change (represented as "*al*" in eq. 1) for irrigated and rainfed maize in the USA. For example, the biophysical analysis by Chung et al. (submitted for publication) implies a reduction of 46% in rainfed maize produced in Ohio. This loss which is represented by "*al*" in Eq. (1) is inputted as maize area loss in 2012 due to the weather extreme in IMPACT. After 2012, the maize area in the USA is brought back to trend by re-adjusting area growth rates. More specifically, the area growth rate is adjusted as follows in 2012:

$$ar = \text{area recovery rate} = \frac{1}{1+al} \tag{1}$$

Since IMPACT involves a partial equilibrium economic model, simulated per capita income would not change from one socio-economic scenario to the next. In reality, the weather extreme, by reducing maize production in the USA, would affect the wages of maize farmers and other agents involved in the maize value chain in the USA. In turn, agricultural GDP and hence national income within the USA would be affected. Since the USA is a major maize producer and exporter across the world, the climate extreme would most likely affect wages in other countries. The effect of the climate extreme on wages would ultimately affect the ability of households at cushioning themselves against increased food insecurity. A multi-country Computable General Equilibrium (CGE) model would be able to capture the effect of the climate

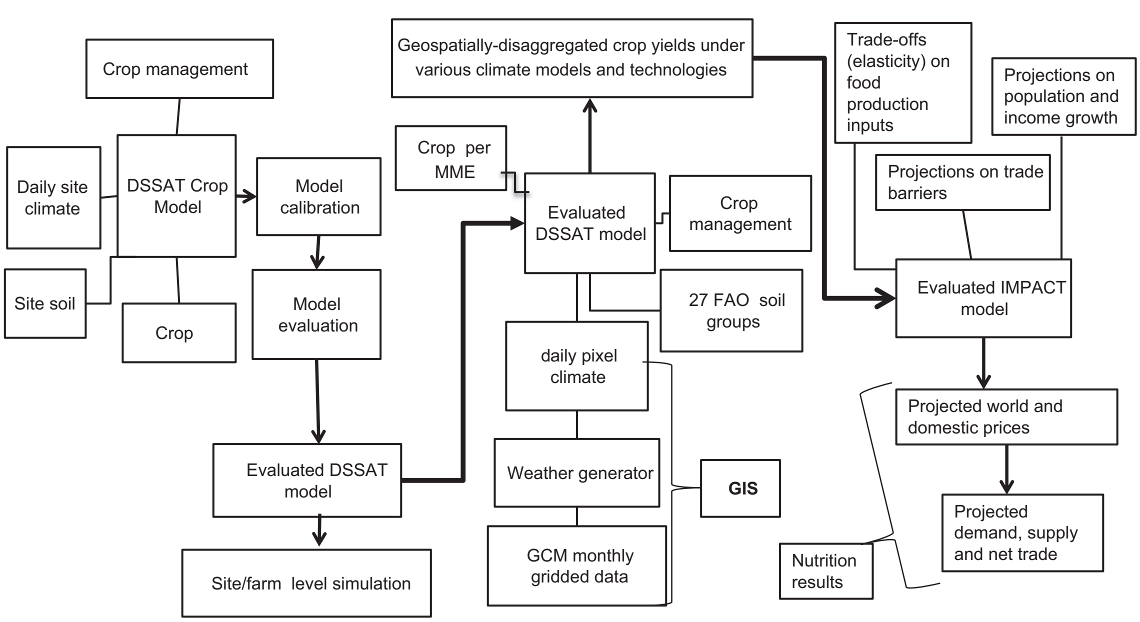

Fig. 1. Illustration of the bio-economic modelling framework; sources consist of authors and adaptation from (Rosegrant et al., 2008).

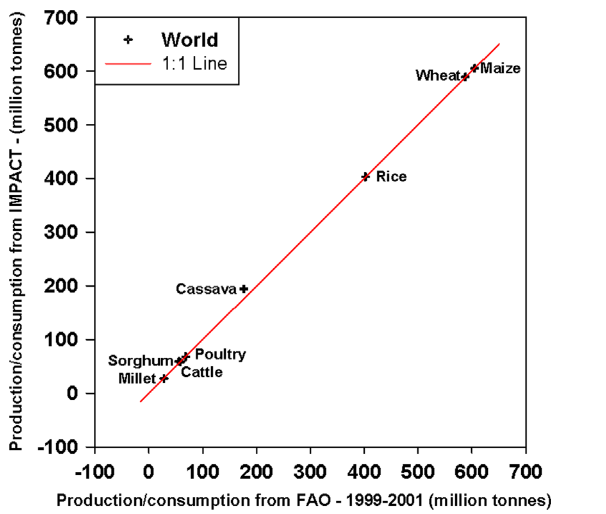

Fig. 2. Validation of IMPACT – simulated versus observed world production/consumption values for selected commodities.

extreme on GDP across world countries, as agricultural and non-agricultural income are endogenous variables in CGE models. IMPACT, a multi-market, multi-country partial equilibrium which focuses on the agricultural sector, estimates the impact of the climate extreme on food availability per capita without assessing the secondary effects of the climate extreme on wages and hence on the ability of households to cushion themselves against increased food insecurity.

IMPACT is well calibrated for baseline food production and consumption across the world: simulated annual production and consumption of selected commodities from IMPACT is similar to FAO's averaged annual production between 1999 and 2001 (Fig. 2).

2.3. Weather extreme scenarios

Six scenarios are analysed in this study. They all involve one socio-economic scenario (Base) which consists of moderate growth in population and world economies between 2000 and 2050. Agricultural technologies are assumed to remain unchanged over the years, although yield improvements from enhanced agronomic practices are considered in the model. Consumers' diets are assumed to change with income growth and higher income is associated with increased consumption of animal-sourced foods.

In the first scenario (Base-2012), the emission of greenhouse gases stops in 2000 such that the projected climate around 2050 is identical to the baseline climate (1950–2000). In the second scenario (Base-2012-EW), the climate extreme occurs in 2012 under the baseline climate (Table 1).

The three other scenarios relate to the 2050s (Table 1). The third scenario (Base-2050) projects the world food system in 2050, under the baseline climate scenario and the base socio-economic scenario. In the fourth and fifth scenarios, namely 'CSI2050-B1-EW' and 'MIR2050-A1-EW', the weather extreme occurs in the USA in 2050 under the CSIRO and MIROC GCMs, respectively. Previous analysis has shown that the combination of the CSIRO-Mk3.0 climate model for 2050 and the B1 emission scenario leads to the mildest changes in the key variables affecting crop growth, namely precipitation and temperature, compared to the baseline climate (Nelson et al., 2010). Similarly, the combination of the MIROC 3.2 climate model with the A1B emission scenario around 2050 leads to the largest changes in mean precipitation and temperature compared to the baseline climate (Nelson et al., 2010). Hence, the range of maize yields in the USA when the weather extreme occurs under climate change and the yield range of other crops on a global scale should all be encompassed by the yields generated under the 'CSI2050-B1-EW' and 'MIR2050-A1-EW' scenarios.

Table 1
Bio-economic scenarios involving a weather extreme.

Scenario name	Socio-economic scenario	Climate model	Emission scenario	Weather extreme (yes/no)
Scenarios for 2012				
Base-2012	Base	Baseline	None	No
Base-2012-WE	Base	Baseline	None	Yes
Scenarios for 2050				
Base-2050	Base	Baseline	None	No
CSI2050-B1-EW	Base	CSIRO-Mk3.0	B1	Yes
MIR2050-A1-EW	Base	MIROC 3.2	A1	Yes

3. Results: impact of the weather extreme on food security

3.1. Impact of the 2012 weather extreme on food security across developing world

Under the 'Base-2012' scenario, maize production in the USA would reach 334 million metric tons in 2012. However, the extreme weather event consisting of combined heat wave and drought would decrease maize production in the USA by 29% compared to the 'Base-2012' scenario. On the other hand, maize consumption in the USA, which would have stood at 244 million metric tons under the 'Base-2012' scenario, would decrease by 5% only due to the weather extreme. Among all maize uses, the consumption of maize as animal feed would experience the largest decrease. The decrease in total maize consumption would be half of that of total maize production in volume terms and this implies that the country will have to reduce its net maize exports to meet its demand requirements. More specifically, net maize exports in the USA would decrease by 83 million tons under the 'Base-2012-EW' scenario compared to the 'Base-2012' scenario (Fig. 3).

The decrease in maize production in the USA due to the weather extreme would act as a negative supply shock across world maize markets. Hence, world maize prices would increase to reflect increased maize scarcity on a global scale. The increased world maize prices would make maize production attractive in other regions not affected by the extreme weather event: they would increase their maize production (Table 2). Across the developing world, E & SE Asia and the LAC region would lead the increase in maize production in volume terms (Table 2). However, the increased maize production in other regions of the world would not be enough to compensate the decrease in maize production in the USA. Hence, global maize production would fall by about 48 million tons compared to the 'Base-2012' scenario; this drop would represent about 6% of global maize production under the 'Base-2012'; scenario. The projected increase in maize production in areas not affected by the weather extreme (Table 2) is likely to be overstated. Some large maize-producing countries, including China, plant maize around the same time as the USA. These countries would not be able to adjust their maize production the year when the weather extreme hits the USA.

The decrease in global maize production would affect maize trade across the globe. All regions across the developing world would reduce their net maize imports. South Asia and the LAC

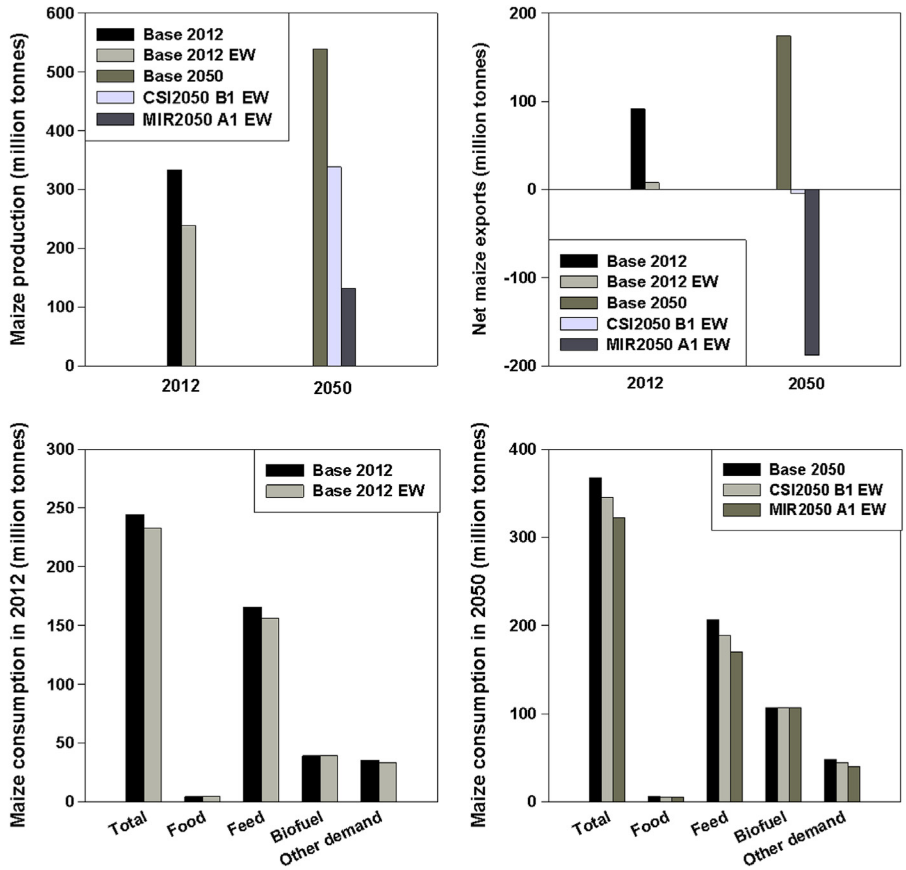

Fig. 3. Projected impact of extreme weather event on maize production consumption and net exports for the USA – results from IMPACT.

Table 2
projected impact of the weather extreme on global maize production and net maize trade – results from IMPACT.

	Production change in million tonnes (%)			Change in net exports in million tonnes (%)		
Region	Base-2012-EW vs Base-2012	CSI2050-B1-EW vs Base-2050	MIR2050-A1-EW vs Base-2050	Base-2012-EW vs Base-2012	CSI2050-B1-EW vs Base-2050	MIR2050-A1-EW vs Base-2050
SSA	4.5 (11)	8.4 (13)	21.1 (32)	9.3 (−94)	23.5 (−47)	51.2 (−102)
CWANA	1.4 (7)	−2.9 (−8)	−5.5 (−16)	2.9 (−18)	1.8 (−5)	4.2 (−10)
South Asia	2.1 (11)	2.2 (5)	11.2 (25)	3.6 (−151)	10.4 (−36)	28.0 (−96)
E & SE Asia	15.4 (8)	18.0 (6)	48.3 (16)	32.9 (−58)	64.1 (−63)	139.9 (−138)
LAC	13.5 (13)	33.6 (16)	42.1 (20)	19.7 (−167)	49.1 (253)	73.3 (377)
USA	−95.4 (−29)	−201.1 (−37)	−407.8 (−76)	−83.8 (−92)	−178.7 (−103)	−362.2 (−208)
ROW	10.4 (11)	21.2 (16)	48.1 (37)	15.4 (288)	29.8 (108)	65.6 (238)
World	−48.1 (−6)	−120.7 (−9)	−242.5 (−18)	0.0 (0)	0.0 (0)	0.0 (0)
	Major net maize exporters in world (million tonnes)					
Country	Base-2012	Base-2012-EW	Country	Base-2050	CSI2050-B1-EW	MIR2050-A1-EW
United States	91.6	7.8	United States[c]	174.0	−4.7	−188.2
Argentina	10.3	13.5	Argentina	20.9	30.7	37.1
Ctr. Eur.[d]	8.1	11.6	Brazil	19.5	48.6	57.8
France[a]	6.0	8.1	Ctr. Eur.[d]	11.7	19.0	22.7
Ukraine[a]	4.7	5.6	Ukraine[a]	11.7	13.7	14.8
Brazil[a]	−4.4	5.3	Russia[a]	8.4	9.9	12.7
Russia[a]	1.8	2.3	France[a]	9.4	9.1	20.6
Vietnam[a]	1.4	2.0	Adriatic[e],[a]	4.1	7.7	8.7
India[a]	−1.5	1.7	China[b]	−55.7	−1.6	60.1
Global exports	127.8	71.9	Global exports	271.0	168.0	291.9

[a] becomes major exporter when climate extreme occurs
[b] become major exporter when climate extreme occurs under MIR-2050-A1-EW only
[c] no longer major exporter when climate extreme occurs in 2050 under climate change
[d] region includes Bulgaria, Czech Republic, Hungary, Moldova, Romania, Slovak Republic, and Slovenia
[e] region includes Albania, Bosnia and Herzegovina, Croatia, Greece, Montenegro, Serbia, and Macedonia

Table 3
Projected impact of climate extreme on global maize consumption – results from IMPACT.

	Food	Feed	Biofuels	Other use	Total	Calorie - base	Caloric change (food)	Caloric change (maize)
Region	Base-2012-EW vs Base-2012 in million tonnes (%)					2012	2012	2012
SSA	−3.7 (−10)	−0.4 (−5)	0.0 (0)	−0.7 (−10)	−4.8 (−9)	2,220.2	−35.3	−39.1
CWANA	−0.5 (−4)	−0.9 (−4)	0.0 (0)	−0.1 (−4)	−1.5 (−4)	2,776.6	−3.9	−5.7
South Asia	−0.7 (−7)	−0.6 (−7)	0.0 (0)	−0.2 (−7)	−1.5 (−7)	2,389.8	−4.8	−3.2
E & SE Asia	−2.2 (−6)	−14.0 (−8)	0.0 (0)	−1.3 (−5)	−17.5 (−7)	3,034.1	−9.5	−7.5
LAC	−1.8 (−7)	−3.6 (−5)	0.0 (0)	−0.8 (−6)	−6.2 (−6)	2,812.9	−28.1	−26.1
USA	−0.3 (−6)	−9.2 (−6)	0.0 (0)	−2.1 (−6)	−11.6 (−5)	3,687.6	−4.4	−6.1
ROW	−0.3 (−5)	−3.9 (−6)	0.0 (0)	−0.8 (−6)	−5.0 (−6)	3,287.0	−1.9	−2.7
Region	CSI2050-B1-EW vs Base-2050 in million tonnes (%)					2050	2050	2050
SSA	−11.3 (−15)	−1.9 (−7)	0.0 (0)	−2.0 (−15)	−15.1 (−13)	2,650.5	−70.3	−54.1
CWANA	−1.1 (−6)	−3.3 (−6)	0.0 (0)	−0.3 (−6)	−4.7 (−6)	3,091.7	−24.9	−8.0
South Asia	−1.3 (−10)	−6.5 (−12)	0.0 (0)	−0.4 (−9)	−8.2 (−11)	2,649.0	−33.3	−4.8
E & SE Asia	−3.7 (−9)	−40.5 (−12)	0.0 (0)	−1.9 (−7)	−46.1 (−11)	3,560.0	−40.5	−12.0
LAC	−3.1 (−10)	−11.2 (−8)	0.0 (0)	−1.3 (−9)	−15.5 (−8)	3,044.5	−59.5	−35.0
USA	−0.5 (−8)	−18.0 (−9)	0.0 (0)	−4.0 (−8)	−22.4 (−6)	4,009.0	−20.3	−9.2
ROW	−0.5 (−8)	−6.9 (−9)	0.0 (0)	−1.3 (−9)	-8.6 (−8)	3,562.5	−23.2	−4.3
Region	MIR2050–A1–EW vs Base-2050 in million tonnes (%)					2050	2050	2050
SSA	−22.4 (−29)	−3.7 (−14)	0.0 (0)	−4.0 (−30)	−30.1 (−26)	2,650.5	−108.0	−107.5
CWANA	−2.4 (−14)	−6.7 (−13)	0.0 (0)	−0.6 (−12)	−9.7 (−13)	3,091.7	−24.9	−17.3
South Asia	−2.8 (−20)	−13.2 (−24)	0.0 (0)	−0.9 (−20)	−16.8 (−23)	2,649.0	−32.0	−10.2
E & SE Asia	−7.8 (−18)	−79.6 (−24)	0.0 (0)	−4.2 (−15)	−91.7 (−23)	3,560.0	−58.8	−25.6
LAC	−6.4 (−20)	−22.1 (−16)	0.0 (0)	−2.7 (−19)	−31.2 (−17)	3,044.5	−121.8	−73.0
USA	−1.0 (−17)	−36.3 (−18)	0.0 (0)	−8.3 (−17)	−45.6 (−12)	4,009.0	−41.4	−19.3
ROW	−0.9 (−16)	−13.8 (−18)	0.0 (0)	−2.7 (−18)	−17.4 (−17)	3,562.5	−13.6	−9.0

region would even become net maize exporters. Under the 'Base-2012' scenario, the leading maize exporters globally in 2012 would be the USA and Argentina. These two countries would account for 80% of global maize exports in 2012, with the USA alone accounting for 72% of global maize exports. With the climate extreme, the USA would become the fourth leading maize exporter by accounting for 8% of global maize exports. India and Brazil, two countries that would have been net maize importers under the 'Base-2012' scenario, would join the list of leading maize exporters. Vietnam would be the only country from E & SE Asia to join the list of major maize exporters (Table 2).

The decrease in global maize production means that global maize consumption would also have to decrease. E & SE Asia would experience the largest decrease in maize consumption in volume terms. However, Africa would experience the largest relative decrease. More specifically, maize consumption in SSA would decrease by 9% compared to the 'Base-2012' scenario. By contrast, E & SE Asia would experience a decrease of 7% (Table 3). The bulk of the reduction in maize consumption would relate to food in SSA. In all other regions of the developing world, the bulk of the reduction in maize consumption would relate to animal feed. The only exception would be South Asia where the consumption of maize as food and feed would decrease by roughly 40% each (Table 3).

One indirect effect of the weather extreme consists of the changes in the demand for maize substitutes and complements. The negative impact of the climate extreme on global maize production would lead to higher maize prices and hence would incite consumers to substitute maize with other products. Another indirect effect of the weather extreme consists of changes in the production of other crops. Maize competes with other crops for the allocation of land and other agricultural inputs. Hence, the increased maize production recorded in countries not affected by the climate extreme should affect the production of other agricultural crops. These two indirect effects should lead to some changes in the production and consumption of other major cereals, namely rice and wheat; and other important staple foods, including cassava in Sub-Saharan Africa. Overall, the production of rice and wheat would increase globally by 2 million tons (Table 4). Such increase reflects a global shift away from the consumption of maize, which has become scarcer and hence more expensive, towards the consumption of other major cereals. CWANA, South Asia and E & SE Asia would increase their production of rice and wheat by a small margin; In SSA and LAC, the production of wheat and rice would be taxed by the increase in maize production (Table 2) and hence would decrease slightly (Table 4). The consumption of rice and wheat would substantially increase everywhere except in South Asia where their consumption would decrease by 89,000 tons compared to the 'Base-2012' scenario. In all other regions of the developing world, the consumption of wheat and rice would increase by 1.2 million tons (Table 4).

The importance of cassava in African diets is illustrated by the fact that Sub-Saharan Africa would experience the highest increase in cassava production and consumption after the weather extreme. More specifically, the sub-region would account for 78% of the increase of 457 thousand tons in world cassava production in 2012 under the 'Base-2012-WE' scenario (Table 4). The sub-region would also increase its cassava consumption by 535 thousand tonnes and would have to rely on imports to meet its consumption requirements (Table 4).

The drop in global maize production coupled with some adjustments in food consumption across the globe would lead to world maize prices increasing by 17% in 2012 if the climate extreme occurs under the baseline climate (Fig. 4). World prices of wheat and rice would also increase, albeit slightly: about 1%, each (Fig. 4).

Daily caloric intake derived from maize would decrease most in SSA compared to other regions of the developing world when the weather extreme affects the USA (Table 3). This, coupled with SSA having the lowest average per capita caloric intake in 2012 (Table 3), suggests that consumers in SSA would find it more difficult to substitute maize for other food products. Hence, the

Table 4
Projected impact of the climate extreme on the production and consumption of rice, wheat and cassava – results from IMPACT.

	Base-2012-EW vs Base-2012	CSI2050-B1-EW vs Base-2050	MIR2050-A1-EW vs Base-2050
Region	Change in production of rice and wheat in thousand tons (%)		
SSA	−8.0 (−0.0)	732.8 (1.7)	−975.2 (−2.2)
CWANA	149.9 (0.1)	−6,018.3 (−3.6)	3,044.9 (1.8)
South Asia	565.5 (0.3)	−16,914.6 (−6.3)	8,746.3 (3.2)
E & SE Asia	555.2 (0.2)	−6,989.6 (−1.8)	17,529.2 (4.6)
LAC	−6.0 (−0.0)	−1,008.3 (−1.6)	−4,266.8 (−6.6)
USA	−16.2 (−0.0)	9,843.7 (10.4)	−7,661.1 (−8.1)
ROW	747.3 (0.3)	9,877.1 (2.3)	−2,362.4 (−0.6)
World	1,987.6 (0.2)	−10,477.2 (−0.7)	14,055.0 (1.0)
	Change in consumption of rice and wheat in thousand tons (%)		
SSA	302.0 (0.8)	−1,660.8 (−1.4)	2,721.6 (2.2)
CWANA	339.8 (0.2)	−363.0 (−0.2)	3,520.7 (1.5)
South Asia	−88.8 (−0.0)	−4,033.0 (−1.4)	−1,034.1 (−0.4)
E & SE Asia	406.6 (0.1)	−3,870.1 (−1.0)	1,874.3 (0.5)
LAC	176.4 (0.3)	−365.4 (−0.6)	748.5 (1.2)
USA	246.9 (0.6)	28.4 (0.0)	1,764.0 (2.8)
ROW	604.8 (0.3)	−213.3 (−0.1)	4,460.0 (1.7)
World	1,987.6 (0.2)	−10,477.2 (−0.7)	14,055.0 (1.0)
	Change in production of cassava in thousand tons (%)		
SSA	356.3 (0.2)	−2,049.6 (−0.8)	1,015.1 (0.4)
CWANA	1.7 (0.3)	7.6 (0.7)	13.5 (1.3)
South Asia	25.4 (0.3)	46.8 (0.4)	531.3 (4.0)
E & SE Asia	8.9 (0.0)	−307.1 (−0.5)	1,380.6 (2.2)
LAC	64.5 (0.2)	1,144.9 (2.1)	−2,152.5 (−3.9)
USA	0.0 (−0.0)	0.0 (0.2)	−0.8 (−9.9)
ROW	0.4 (0.1)	147.3 (23.0)	271.0 (42.4)
World	457.1 (0.2)	−1,010.1 (−0.3)	1,058.3 (0.3)
	Change in consumption of cassava in thousand tons (%)		
SSA	535.2 (0.4)	−180.3 (−0.1)	2,074.8 (0.8)
CWANA	2.0 (0.1)	−14.5 (−0.6)	−4.0 (−0.2)
South Asia	−15.3 (−0.2)	−69.0 (−0.7)	−110.5 (−1.1)
E & SE Asia	14.3 (0.0)	−74.4 (−0.1)	−38.1 (−0.1)
LAC	−88.8 (−0.2)	−615.8 (−1.3)	−827.1 (−1.7)
USA	0.2 (0.1)	−1.7 (−0.7)	−2.2 (−0.9)
ROW	9.5 (0.1)	−54.2 (−0.8)	−34.7 (−0.5)
World	457.1 (0.2)	−1,010.1 (−0.3)	1,058.3 (0.3)

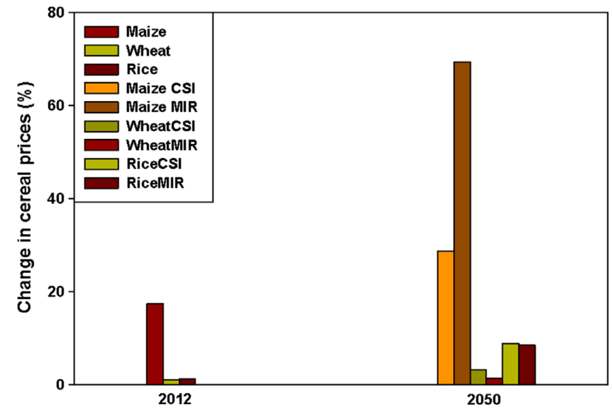

Fig. 4. Projected impact of the climate extreme on key cereal prices.

effects of the weather extreme on food security would likely be worst in SSA. Another region that would experience a substantial decrease in caloric intake from maize is the LAC region; however, its average per capita daily caloric intake, under the 'Base-2012' scenario, would be much higher than that of SSA (Table 3).

The number of people at risk of hunger would increase most in SSA, the region that would also experience the largest decrease in per capita caloric availability due to the weather extreme. Within SSA, countries that would experience an increase of 1 million or more in the number of people at risk of hunger would mainly be from Eastern Africa and would consist of Kenya, Tanzania, Ethiopia, Malawi, Zambia, Zimbabwe and the Democratic Republic of Congo (Fig. 5).

Despite experiencing larger reductions in per capita caloric availability, Malawi would have a smaller increase in the number of people at risk of hunger compared to Kenya and Tanzania (Fig. 5). The higher population levels in Kenya and Tanzania would explain this result. Kenya, Tanzania and Malawi would have similar per capita caloric intake in 2012 under the 'Base-2012' scenario with 2070, 2081 and 2018 calories, respectively. Hence, their shares of people at risk of hunger would be similar: they would stand at 30, 27 and 34 for Kenya, Tanzania and Malawi, respectively. However, the population in each of Kenya and Tanzania would be twice as high as that of Malawi. More specifically, Kenya, Tanzania and Malawi would have about 43, 48 and 16 million people, respectively. The combination of similar per capita caloric intake across the 3 countries and a much smaller population in Malawi implies that the weather extreme would lead to a smaller increase in the number of at-risk people in Malawi, even if the country experiences a larger reduction in caloric intake, compared to Kenya and Tanzania. However, in relative terms, the effect of the weather extreme would be more severe in Malawi compared to Kenya or Tanzania. The relative increase in the number of people at risk of hunger would be 24% in Malawi compared to the 'Base-2012' scenario; it would stand at 19 and 17% in Kenya and Tanzania, respectively. Relative values do away with the effect that population levels can have on estimating the impact of the weather extreme.

Ethiopia and Zambia would also have similar daily per capita caloric intake in 2012, under the 'Base-2012' scenario; however, the Ethiopian population would be 6 times higher than that of Zambia. Hence, the weather extreme would lead to Ethiopia having a higher increase in the number of people at risk of hunger (Fig. 4), although its relative effect would be more severe in Zambia which would experience a higher reduction in caloric intake due to the weather extreme. In relative terms, the increase in the number of people at risk of hunger would be 20% in Zambia and 5% in Ethiopia.

Lesotho, which would experience the largest reduction in caloric intake in SSA would also account for the largest relative increase in the number of people at risk of hunger: 46%. Lesotho would be followed by South Africa which would experience a relative increase of 41% in the number of people at risk of hunger. South Africa and Tanzania would have similar population sizes in 2012. They would also experience a similar reduction in per capita caloric intake due to the weather extreme (Fig. 5). However, South Africa would have a higher per capita caloric intake which would ensure that a smaller portion of its population would be at risk of hunger in 2012 under the 'Base-2012' scenario. The higher caloric intake in South Africa would also dampen the negative effect of the weather extreme on the number of people at risk of hunger (Fig. 5). In relative terms, South Africa would experience a larger increase in the number of people at risk of hunger compared to Tanzania, due to its smaller population at risk of hunger under the 'Base-2012' scenario.

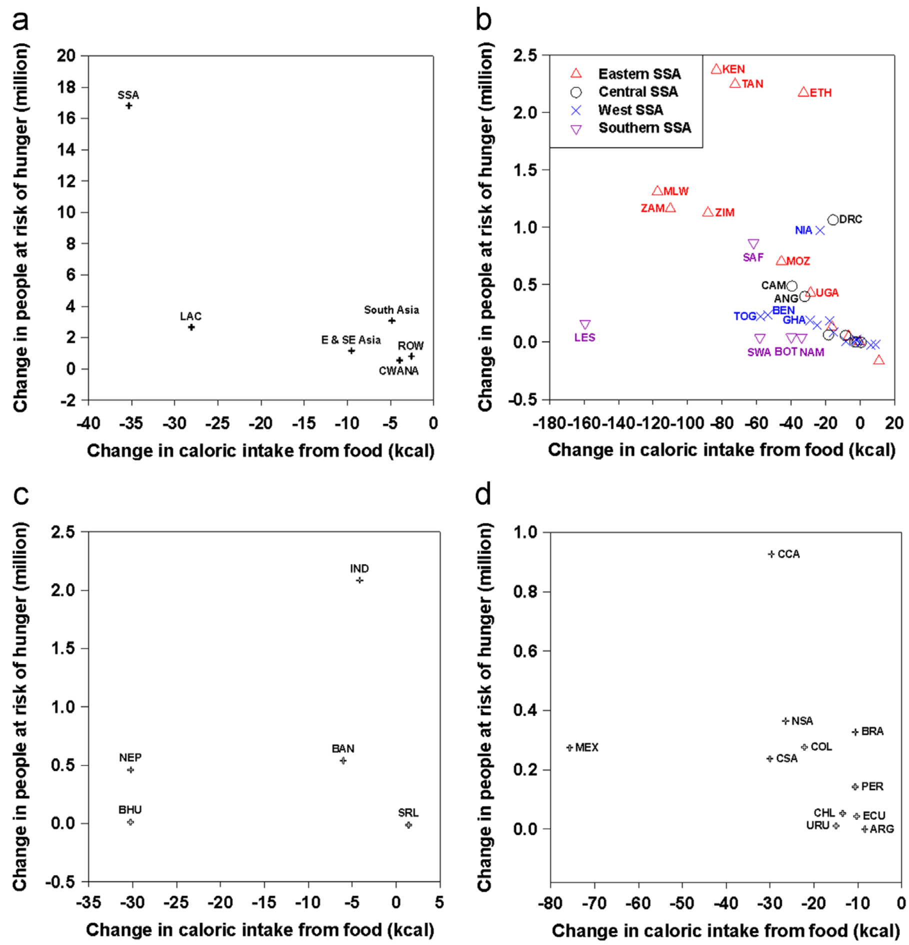

Fig. 5. Projected impact of extreme weather event on number of people at risk of hunger in 2012 – results from IMPACT. CCA region includes Belize, Costa Rica, Cuba, Dominican Republic, El Salvador, Guatemala, Haiti, Honduras, Nicaragua, and Panama; CSA includes Bolivia and Paraguay; NSA includes French Guiana, Guyana, Suriname and Venezuela. (a) World, (b) SSA, (c) south asia and (d) LAC.

The LAC region, which would experience the second largest decrease in per capita caloric availability due to the weather extreme, would see an increase of 2.6 million in the number of people at risk of hunger. Within the LAC region, countries from the Caribbean and Central America (CCA) would be hardest-hit, despite experiencing a smaller decrease in per capita caloric intake compared to Mexico (Fig. 5). In 2012, prior to the weather extreme, Mexico would have a higher daily per capita caloric intake compared to CCA; the caloric intake levels would stand at 3124 and 2458 in Mexico and CCA, respectively. Hence, CCA would have a higher share of its population at risk of hunger: 21% in CCA versus 5% in Mexico. These would correspond to 16 million people at risk of hunger in CCA versus 5.8 million in Mexico whose population would be 1.5 times higher than that of CCA in 2012. The weather extreme would lead to a higher reduction in caloric intake in Mexico; however, its effect of food security would not be worse in Mexico compared to CCA, because of the less precarious food security situation in Mexico, prior to the weather extreme. In relative terms, the increase in the number of people at risk of hunger caused by the weather extreme would be higher in CCA compared to Mexico: 5.8 versus 4.8%.

Across the LAC region, few other countries CSA, NSA, Chile, Uruguay, and Colombia would experience a higher relative increase in the number of people at risk of hunger compared to CCA (Fig. 5). CSA and NSA would have the highest relative increase in the number of people at risk of hunger with a value of 8.5%, each. Chile, Uruguay, and Columbia would follow with increases of 7.2%, 7%, and 6%, respectively.

In the CSA and NSA regions, caloric intake in 2012 prior to the weather extreme would be smaller than that of CCA. The decrease in food caloric intake brought by the weather extreme in the CSA and NSA regions would be similar to that of the CCA region. Hence, the proportional increase in the number of people at risk of hunger would be lower in CCA compared to CSA and NSA.

Chile, Colombia and Uruguay would have a higher caloric intake compared to CCA prior to the weather extreme. Hence, compared to the CCA region, these three countries would have a smaller proportion of their population that would be at risk of hunger prior to the weather extreme. In addition, each of Chile, Colombia and Uruguay would have a much smaller population compared to the CCA region. Hence, the proportional increase in the number of people at risk of hunger due to the weather extreme would be higher in these three countries compared to CCA.

Interestingly, South Asia, where the reduction in caloric intake would be less than one-sixth of that of SSA, would be the second hardest-hit region in terms of food insecurity; the number of people at risk of hunger in this region would increase by 3 million due to the weather extreme. India alone would account for more than two-thirds of the increase in the number of at-risk people in South Asia, despite experiencing a reduction in caloric intake that would be substantially less than that of Nepal or Bhutan (Fig. 5).

The very high population in India explains why the increase in the number of people at risk of hunger would be much higher in value terms compared to Nepal or Bhutan. By 2012, India's population would stand at around 1.2 billion; in Nepal and Bhutan, the population numbers would stand at 31 million and 749 thousand, respectively. Prior to the weather extreme, daily per capita caloric intake would be higher in India than in Nepal and Bhutan. The values would be 2423, 2296 and 2229 in India, Nepal and Bhutan, respectively. Hence, the share of the population at risk of hunger would be lower in India; these shares would be 17%, 18% and 28% in India, Nepal and Bhutan, respectively. In relative terms, the impact of the weather extreme on the number of people at risk of hunger would be slightly higher in Nepal than in Bhutan: 8% and 6%, respectively. By contrast, India would experience a 1% increase in the number of people at risk of hunger due to the weather extreme. Apart from Bhutan and Nepal, Bangladesh would also have a higher relative increase in the number of people at risk of hunger compared to India.

Surprisingly, despite experiencing the largest reduction in maize consumption across the developing world (Table 3), E & SE Asia would not experience a substantial reduction in caloric intake compared to SSA and the LAC region (Fig. 5). This is mainly caused by the fact the bulk of the reduction in maize consumption in E & SE Asia would consist of a reduction in animal feed. In addition, the region would have the highest base caloric intake in 2012 without the weather extreme, among all developing regions (Table 3). Hence, E & SE Asia would experience the fourth largest increase in the number of people at risk of hunger, in both value and relative terms. The region would be ranking behind SSA, LAC and South Asia.

3.2. Results – impact of a 2050 weather extreme on global food security

Under the 'Base-2050' scenario, the world economies are projected to experience moderate growth in per capita income between 2000 and 2050. Under such scenario, countries which were ranked as developing countries in 2012 might no longer be considered as such in 2050. Hence, in this section, they are referred as developing countries/regions of 2012.

Under the 'Base-2050' scenario, global maize production would almost double by 2050 compared to 2012. Just like in the 2000s and 2010s, the USA would remain the leading maize producer and exporter in the world in 2050: the country would account for 40% and 64% of global maize production and exports, respectively (Table 2). Hence, an extreme weather event that would affect maize production in the USA in 2050 could still have serious repercussions for food security in vulnerable regions.

If the weather extreme occurs in 2050 instead of 2012, its effects on maize production in the USA would be more pronounced. More specifically, the reduction in maize production caused by the weather extreme would range between 37% under the 'CSI2050-B1-EW' climate scenario and 76% under the 'MIR2050-A1-EW' climate scenario. However, maize consumption in the USA would barely decrease. In this case, the country would have to become a net maize importer to meet its consumption requirements: its net maize imports would range between 4.6 and 19 million tons (Fig. 3).

The substantial decrease in maize production in the USA in 2050 coupled with sustained maize consumption within the country would translate into high maize prices that would incite other countries not affected by the climate extreme, to increase their maize production (Table 2). Maize production would increase everywhere, except in the CWANA region (Table 2) where maize would still not be a key food product in 2050 (Table 3). However, despite the increased maize production in countries not affected by the climate extreme, global maize production would still decrease by 9% to 18%, compared to the 'Base-2050' scenario.

By 2050, under the 'base-2050' scenario, the USA, Argentina, Brazil and Central Europe would lead global maize exports and would account together for 80% of global maize exports. However, the weather extreme would force the USA out of the list of the major maize exporters in 2050; other countries that would become major maize exporters globally would mainly come from the European continent (Table 2).

The weather extreme in 2050 would reduce global maize consumption. E & SE Asia would experience by far the largest reduction in maize consumption in volume terms (Table 3). In addition, the reduction in maize consumption in this region would mainly affect animal feed. SSA and the LAC region would be next, relative to the reduction in maize consumption. In each of these regions, maize consumption would decrease by 15–30 million tonnes due to the weather extreme. In SSA, the bulk of the reduction would relate to human food whereas in the LAC region, it would relate to animal feed (Table 3).

If the weather extreme occurs in 2050 under the milder climate change scenario, the decrease in global maize production would be accompanied by a decrease in the production of wheat and rice. This implies that the increased demand for rice and wheat brought by the weather extreme would not be strong enough to increase the production of these two commodities. Overall, the consumption of rice and wheat would decrease across all world regions, except the USA, where it would remain stagnant (Table 4). Similarly, the production of rice and wheat would decrease across most regions of the developing world of 2012, except in SSA, which would experience an increase in the production of maize, rice and wheat under the weather extreme (Table 4). In South Asia, E & SE Asia and LAC, the increase in maize production brought by the weather extreme would be accompanied by a decrease in the production of rice and wheat (Table 4).

The weather extreme would see SSA increase its production of key cereals in 2050 under the milder climate change scenario. This increase would come at the expense of reducing the production of other crops, including cassava. More specifically, the sub-continent would lead all regions relative to the reduction in cassava production (Table 4). SSA would also experience the second-largest reduction in cassava consumption if the weather extreme occurs in 2050 under the milder climate change scenario (Table 4). The LAC region would experience the largest increase in cassava production and the largest reduction in cassava consumption if the weather extreme occurs under the milder climate change scenario (Table 4). Since the region was a net cassava exporter prior to the weather extreme (data not shown), the change in its cassava production and consumption would be used as exports to other regions.

If the weather extreme occurs in 2050 under the harsher climate change scenario, the decrease in global maize production would be accompanied by an increase in the global consumption of rice and wheat (Table 4). In addition, the changes in the production and consumption of rice and wheat across the developing world would be similar to those that would occur, if the weather extreme occurred in 2012.

If the weather extreme occurs under the harsher climate change scenario, SSA would increase its consumption of not only rice and wheat, but also cassava. The sub-continent would increase its cassava consumption by more than 2 million tons; it would also be the only region that would experience an increase in cassava consumption due to the weather extreme (Table 4). Cassava production would also increase in the SSA (Table 4), but the sub-continent would still need to rely on imports to meet its consumption requirements. In the LAC region, the increase of 42

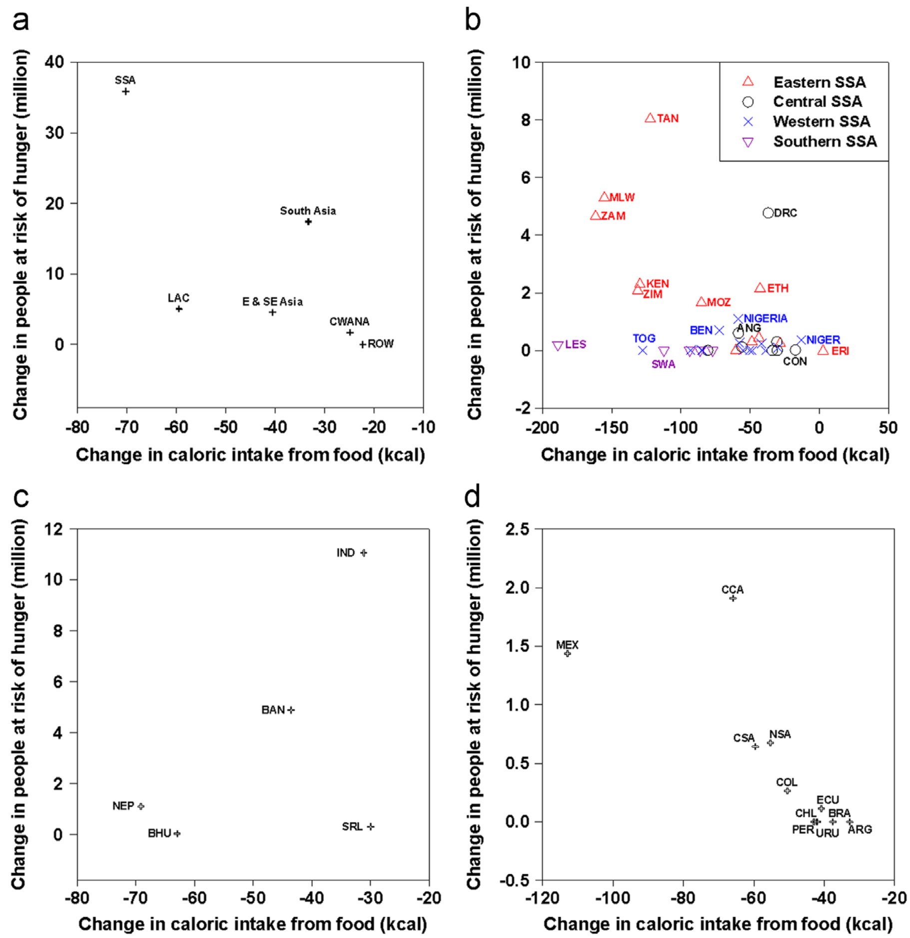

Fig. 6. Projected impact of the extreme weather event on number of people at risk of hunger under the CSI2050 A1 EW scenario – results from IMPACT. CCA region includes Belize, Costa Rica, Cuba, Dominican Republic, El Salvador, Guatemala, Haiti, Honduras, Nicaragua, and Panama; CSA includes Bolivia and Paraguay; NSA includes French Guiana, Guyana, Suriname and Venezuela. (a) World, (b) SSA, (c) south asia and (d) LAC.

million tons in maize production would come at the cost of reducing the production of other crops, including rice, wheat and cassava. Cassava production would decrease by more than 2 million tons whereas the production of combined rice and wheat would decrease by 7.6 million tons (Table 4).

If the climate extreme occurs in 2050 under climate change, maize prices in the long run would increase by 30% to 70%, compared to the ‘Base-2050’ scenario (Fig. 4). Long-run prices for wheat would increase from 1% to 3% whereas long run prices for rice would increase from 8% to 9% (Fig. 4). Interestingly, the prices of rice and wheat would be higher if the weather extreme occurred under the milder climate change scenario compared to the harsher climate change scenario. The higher prices, related to the milder climate change scenario, are partly fuelled by the decrease in the global production of rice and wheat when the weather extreme occurs under the milder climate change scenario (Table 4).

Despite experiencing the largest reduction in maize consumption under the weather extreme, E & SE Asia would rank below SSA, South Asia and the LAC region, in the number of people at risk of hunger (Figs. 6 and 7). The combination of the highest base caloric intake in 2050 and relatively small reductions in caloric intake due to the weather extreme in E & SE Asia would explain this result. The reduction in maize consumption in E & SE Asia would mainly consist of a reduction in animal feed (Table 3). This would translate into a smaller reduction in caloric intake compared to other regions such as SSA where the bulk of the reduction in maize consumption would consist of a reduction in food (Table 3).

SSA would experience the largest increase in the number of people at risk of hunger, if the weather extreme occurs in 2050 under climate change (Figs. 6 and 7). The region would be unique in combining one of the lowest caloric intakes by 2050 with one of the highest reductions in caloric intake due to the weather extreme (Table 3). The increase in the number of people at risk of hunger in SSA would range between 36 and 66 million people. In relative terms, the number of people at risk of hunger in SSA would rise by 14% to 26% compared to the ‘Base-2050’ scenario.

If the weather extreme occurs under the milder climate change scenario, the countries within SSA that would experience an increase of 1 million or more in the number of people at risk of hunger are Tanzania, Malawi, Zambia, the Democratic Republic of Congo, Kenya, Zimbabwe, Ethiopia, Mozambique and Nigeria (Fig. 6); most of them would be in East Africa. However, if the weather extreme occurs under the harsher climate change scenario, more countries would experience an increase of at least 1 million in the number of people at risk of hunger. Additional countries that would join the countries listed above are Angola in Central Africa; and Benin and Togo in West Africa (Fig. 7).

In relative terms, the countries in SSA that would experience the largest increases in the number of people at risk of hunger under the weather extreme would also be located in eastern Africa. If the weather extreme occurs under the milder climate change scenario, countries with the largest relative increase in the

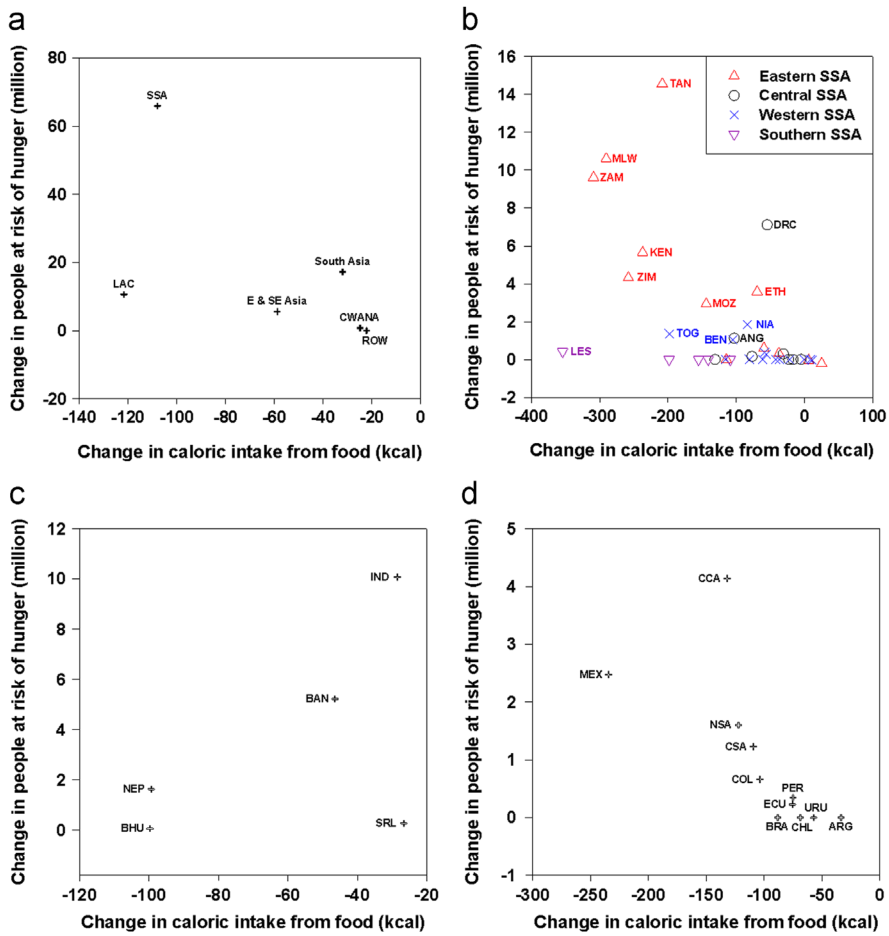

Fig. 7. Projected impact of the extreme weather event on number of people at risk of hunger under the MIR2050 B1 EW scenario – results from IMPACT. CCA region includes Belize, Costa Rica, Cuba, Dominican Republic, El Salvador, Guatemala, Haiti, Honduras, Nicaragua, and Panama; CSA includes Bolivia and Paraguay; NSA includes French Guiana, Guyana, Suriname and Venezuela. (a) World, (b) SSA, (c) south asia and (d) LAC.

number of people at risk of hunger would be Gambia in West Africa with an increase of 163% and Lesotho in southern Africa with an increase of 68%. These two countries would be followed by Kenya, Tanzania, Zambia, Malawi, Mozambique and Zimbabwe with 59%, 45%, 36%, 34%, 29%, and 23%, respectively. If the weather extreme occurs under the harsher climate change scenario, Togo in West Africa would experience the highest relative increase with 305%; it would be followed by Gambia in West Africa with 163%, Lesotho in southern Africa with 148%. Kenya, Tanzania, Zambia, Malawi, Mozambique and Zimbabwe would follow with an increase of 146%, 82%, 76%, 68%, 52% and 47%, respectively.

In southern Africa, only Lesotho would experience an increase in the number of people at risk of hunger, if the weather extreme occurs in 2050 under climate change (Figs. 5 and 6). More specifically, the number of people at risk of hunger would rise by 200 thousand under the milder climate change scenario to 421 thousand under the harsher climate change scenario (Fig. 6). If the weather extreme occurs under the milder climate change scenario (CSI2050-A1-EW), daily caloric intake would decrease by 112, 93, 86 and 77, in Swaziland, South Africa, Botswana and Namibia, respectively (Fig. 6). The reductions in caloric intake would be larger under the harsher climate change scenario. However, none of these countries would experience an increase in the number of at-risk people (Figs. 6 and 7). This implies that by 2050, daily caloric intake in all of southern Africa, Lesotho excluded, would have risen enough to offset the negative effect of the weather extreme on national food security.

In Central Africa, 3 countries, namely Cameroon, Equatorial Guinea and Gabon, would experience no increase in the number of people at risk of hunger is the weather extreme occurs under the milder climate change scenario (Fig. 6). Among these three countries, Cameroon would experience the largest decrease in caloric intake whereas Equatorial Guinea would experience the lowest decrease. In these three countries too, average per capita caloric intake would have risen enough by 2050 to counter the negative effects of the weather extreme on national food security. Among all 3 countries, oil-producing Gabon would be the richest by 2050 with a per capita income that would be 4 times higher than that of Equatorial Guinea and 7 times higher than that of Cameroon. Gabon would also be having the highest caloric intake prior to the weather extreme: 3411 calories per capita. If the weather extreme occurred in 2050 under the harsher climate change scenario, the same three countries would see no increase in their number of people at risk of hunger (Fig. 7). In all other countries in Central Africa, the weather extreme would worsen national food security under any of the climate change scenarios. These countries are Angola, Central African Republic, Chad, Congo and the Democratic Republic of Congo. Moreover, in all these countries, except Congo, the reduction in caloric intake brought by the weather extreme would be higher under the harsher climate change scenario compared to the milder scenario (Figs. 6 and 7).

In half of all western African countries, food security would not worsen if the climate extreme occurs in 2050 under the milder climate change scenario. These countries include Ghana, Guinea,

Guinea Bissau, Côte d'Ivoire, Mali, Senegal, and Sierra Leone. Benin would experience the second largest increase in the number of people at risk of hunger in West Africa. The country would experience an increase of 700,000 people and it would be followed by Niger with 360,000, Gambia with 260,000 and Burkina Faso with 240,000 (Fig. 7).

Apart from Togo, all other countries in West Africa that did not experience an increase in the number of people at risk of hunger under the milder climate change would have the same outcome under the harsher climate change scenario (Fig. 7). In Togo, the reduction in caloric intake would rise from 127 under the milder climate change scenario to 200 under the harsher climate change scenario. As a result, the number of people at risk of hunger would rise from 0 under the milder scenario to 1.4 million under the harsher scenario. In Benin, Burkina Faso and Nigeria, the increase in number of people at risk of hunger would be worse if the weather extreme occurs under the harsher climate change scenario compared to the milder scenario. More specifically, under the harsher climate change scenario, the number of people at risk of hunger would rise to 1 million, 360,000 and 1.8 million in Benin, Burkina Faso and Nigeria, respectively (Fig. 7). In the other countries, namely Gambia, Liberia and Niger, the increase in the number of people at risk of hunger would be smaller if the weather extreme occurs under the harsher climate change scenario compared to the milder scenario. In Gambia and Niger, under the harsher climate change scenario, the number of people at risk of hunger would rise to 260,000 and 4000 people, respectively; it would decrease by 31,000 people in Liberia (Fig. 7).

Within the LAC region, the number of people at risk of hunger would rise from 5 million under the milder climate change scenario to 11 million under the harsher climate change scenario (Figs. 6 and 7). This result suggests that, as the momentum of climate change worsens, the negative effect of the weather extreme on food security in the LAC region would also worsen.

Within the LAC region, the Caribbean Central America and Mexico would be hardest-hit: the number of people at risk of hunger would increase by 2–4 million in CCA and by 1.4–2.5 million in Mexico (Figs. 6 and 7). In relative terms, CCA would experience an increase of 13–28% in the number of people at risk of hunger compared to the 'Base-2050' scenario. In Mexico, the change in the number of people at risk of hunger would range from 25% to 43%. The higher at-risk population in CCA, under the 'Base-2050' scenario, explains why the weather extreme would lead to a higher increase in the number of people at risk of hunger, despite CCA experiencing smaller reductions in per capita caloric intake compared to Mexico.

By 2050, under the 'Base-2050' scenario, Mexico would have a substantially higher daily per capita caloric intake compared to CCA, even if the latter would have seen an improvement in food security between 2012 and 2050. Indeed, average per capita daily caloric intake under the baseline climate model would be 2700 by the year 2050, compared to 2460 in the year 2012 for the CCA. In Mexico, per capita caloric intake would remain high by 2050 and would barely change between 2012 and 2050; it would increase from 3100 to 3200. By 2050, Mexico would also have a slightly larger population compared to CCA, under the baseline climate model: 144 versus 109 million people. The substantially higher caloric intake in Mexico coupled with a slightly higher population leads to Mexico having a lower at-risk population compared to CCA by 2050, under the baseline climate model. Indeed, by 2050, under the 'Base-2050' scenario, the number of people at risk of hunger would reach 14 million in CCA; it would reach 5.8 million in Mexico.

In other regions not as populous as CCA, the relative increase in the number of people at risk of hunger would be very high, despite these regions experiencing reductions in caloric intake similar to those of CCA and also sharing similar per capita caloric intake in 2050 under the 'Base-2050' scenario. NSA and CCA would share similar daily per capita caloric intake by 2050, under the 'Base-2050' scenario: 2700. Moreover, the reductions in caloric intake caused by the weather extreme would be similar across the two regions (Figs. 6 and 7). Yet, CCA would experience a higher increase in the number of people at risk of hunger (Figs. 6 and 7). However, the relative increase in the number of people at risk of hunger in NSA would range between 34% and 80% and hence, would be much higher than that of CCA. The higher population in CCA explains this result: by 2050, the population would be 44 million in NSA compared to 108 million in CCA.

South Asia would also be the second hardest-hit region after SSA, if the weather extreme occurred in 2050, instead of 2012: the number of people at risk of hunger would rise by 17 million people (Figs. 6 and 7). The largest increase in the number of people at risk of hunger would occur in India. Interestingly, the reduction in caloric intake in India would be less than half that of Nepal and yet, India would experience an increase of 10–11 million in the number of at-risk people, unlike Nepal which would experience an increase of 1.1–1.6 million (Figs. 6 and 7). The higher population in India explains these results. The two countries would have similar average per capita caloric intake by 2050, under the 'Base-2050' scenario. In India, daily caloric intake would stand at 2700; in Nepal, it would stand at 2500. However, India's population would reach 1.7 billion by 2050, whereas Nepal's population would reach 46 million. In relative terms, the increase in the number of at-risk people in India would range between 8% and 7% compared to a scenario involving perfect climate change. In Nepal, the increase would range between 28 and 41%.

4. Discussion

USDA's estimates are in agreement with the simulated results on annual maize production and consumption in the USA in 2012, after the weather extreme. Based on USDA's estimates, annual maize production in the USA was estimated at 314 million tons in the 2011/12 season; world maize production stood at around 881 million tons over the same period (Foreign Agricultural Service, 2012). Hence, the share of the USA in global maize production was around 36%. Based on the simulated results from IMPACT, the projected share of the USA in global maize production after the weather extreme in 2012 would be 32%. The simulated results from IMPACT imply that US maize production in 2012, after the weather extreme, would be about 238 million tons and world maize production would stand at 741 million tons.

Similarly, the estimates from USDA suggest that, with a consumption volume of 279 million tons in 2012, the USA accounted for 32% of global maize consumption (Foreign Agricultural Service, 2012). The simulated results from IMPACT imply that, with the weather extreme in 2012, US maize consumption would stand at 244 million and would account for 33% of global maize consumption.

However, the estimates from USDA differ substantially from those of IMPACT on maize trade volumes. The simulated results from IMPACT imply that, with net maize exports amounting to 8 million tons under the weather extreme in 2012, the US would account for 11% of world maize exports. By contrast, USDA's estimates imply that net maize exports in the USA amounted to 14 million tons and the country accounted for 20% of global maize exports in 2012 (Foreign Agricultural Service, 2012). In addition, maize exports from the USA were much lower in 2012 than in earlier years (Chung et al., submitted for publication); they were also accompanied by a substantial decrease in US maize stocks, compared to earlier years (Chung et al., submitted for publication).

The simulated results from IMPACT imply that the change in US maize stocks remains the same over the years, with or without the weather extreme. Such discrepancy between USDA's estimates and the simulated results from IMPACT reflect the limitations of IMPACT, a partial equilibrium model that assumes that changes in population, income and food stocks are exogenous. The projected substantial decrease in net maize exports from the USA would lead to substantial but unrealistic effects on food security across the globe. Hence, the magnitude of the results from IMPACT should be used with caution; however, the trends observed in the results are likely to be valid.

The study results demonstrate that climate extremes that negatively affect crop production among major world exporters can indeed have negative effects on food security in other regions. The study results imply that across the developing world, Sub-Saharan Africa, South Asia and the LAC region are likely to suffer most from the climate extreme that occurred in the USA, in 2012. Within SSA, the countries that would experience the highest increase in the number of people at risk of hunger due to the weather extreme would mainly be from eastern Africa; however, the countries that would experience the highest relative increase in the number of at-risk people would include countries from eastern and southern Africa; these countries, which would experience an increase of 10% or more in the number of at-risk people, would be Lesotho, South Africa, Malawi, Zambia, Kenya, Tanzania, Swaziland, Zimbabwe, Uganda and Bostwana. Within the LAC region, the CCA would experience the largest increase in the number of people at risk of hunger due to the weather extreme; however, in relative terms, CSA, NSA, Chile, Uruguay and Colombia, would also see their food security worsen due to the weather extreme. Within South Asia, India alone would account for two-thirds of the increase in the number of people at risk of hunger. Other countries that would experience substantial increases in their number of at-risk people include Nepal and Bhutan.

The relative effects of the weather extreme on long-run maize production would be worse if it occurred in 2050 instead of 2012. The negative impact of the weather extreme on maize production in the USA and hence on global maize production would be much worse in 2050 than in 2012. With the non-implementation of climate change adaptation strategies across the world food baskets between the 2000s and 2050s, climate change would be eroding crop productivity gains over the years. Hence, the weather extreme in 2050 would further weaken maize productivity in the USA, which is projected to remain the leading maize producer and exporter in 2050.

Similarly, the negative effects of the weather extreme on food security would be worse if it occurred in 2050 compared to 2012. Globally, the relative increase in the number of people at risk of hunger would be 1.4% in 2012; if the weather extreme occurred in 2050, the relative increase in the number of at-risk people would range between 8% and 13%. However, the hardest-hit regions would remain the same, whether the weather extreme occurs in 2012 instead of 2050: SSA, South Asia and the LAC region. Across these regions, food security would improve between 2012 and 2050, under the baseline climate model and moderate growth in per capita income across world economies. In few countries located in southern, western and central Africa, and in the LAC region, per capita caloric intake would have risen enough to offset the negative effects of the weather extreme. However, in the other countries of SSA, South Asia and the LAC region, the weather extreme would erode much of the gains made in food security.

The effect of the weather extreme on food security in vulnerable countries can be mitigated through social protection programs including cash transfers and food aid (Chung et al., submitted for publication). By 2012, the LAC region had strong social protection programs (Ferreira and Robalino, 2010) which likely mitigated the negative effect of the weather extreme on food security in the region. Another strategy for enhancing the adaptive capacity of countries to weather extremes would consist of changing policies that favour the use of maize or other food crops for biofuel production. The proportion of US maize production used for ethanol production increased from 1% in the 1980s to 25% in 2007/2008 (Piesse and Thirtle, 2009; Capehart, 2014). The increase was fuelled in part by favourable US policies (Yano et al., 2010; Capehart, 2014). Some of the maize used in ethanol production could be diverted into replenishing US maize stocks which could be used to buffer the production loss brought by weather extremes.

Our results illustrate the considerable utility of the process-based spatial bio-economic framework, as a tool for assessing the impacts of extreme weather events. The socio-economic model (IMPACT) is calibrated for the year 2000 and assumes moderate growth in per capita income followed by the 2012 weather extreme. The results from the model were close to the reality despite the fact that it is unlikely that moderate economic growth was observed across the whole world between 2000 and 2012. Two major events, the global food price crisis in 2008 which was followed by the global financial crisis, were not captured in model. These events had large influence on global food prices and farmers' decisions. Similarly, speculation was not captured in model.

5. Conclusion

One of the objectives of this study was to quantify the potential effects of the 2012 weather extreme in the USA on food security across the developing world. Study results suggests that the extreme climate of 2012 that occurred in the USA is likely to increase food insecurity among poor communities where maize provides a substantial portion of daily caloric intake and where households cannot easily adjust their food consumption patterns in the face of increased maize scarcity. Our results indicate that countries where food security would worsen due to the weather extreme are located in eastern and southern Africa; South Asia; and the LAC region.

If a similar weather extreme were to occur in the USA in 2050 under climate change, its effects on global food production and security would be worse, assuming no adaptation to climate change over the years. In addition, the hardest-hit regions would remain the same, whether the weather extreme occurs in 2012 instead of 2050: SSA, South Asia and the LAC region. However, for few countries in Sub-Saharan Africa and LAC, per capita caloric intake would have risen enough to completely offset the negative effect of the weather extreme on food insecurity.

Future research would involve developing a CGE model that can consider the spillover effects of weather extremes. Similarly, frequency distribution on weather extremes could be used in combination with a CGE model to project the impact of climate extremes in the future.

Acknowledgements

This research was supported by the CGIAR research programme on Climate Change, Agriculture and Food Security (CCAFS).

References

Adger, W.N., 1999. Social Vulnerability to Climate Change and Extremes in Coastal Vietnam. World Dev. 27 (2), 249–269.

Ahmed, A.S., Diffenbaugh, S.N, Hertel, W.T., 2009. Climate volatility deepens poverty vulnerability in developing countries. Environ. Res. Lett. 4 (3), 8.

Boyer, J.S., Byrne, P., Cassman, K.G., et al., 2013. The U.S. drought of 2012 in perspective: a call to action. Glob. Food Secur. 2 (3), 139–143.
Brown, M.E, Funk, C.C., 2008. Food security under climate change. Science 319 (5863), 580–581.
Capehart, T., 2014. Corn Policy. 2014. From ⟨http://www.ers.usda.gov/topics/crops/corn/policy.aspx#.U23shygr00G⟩.
Changnon, S., 2003a. Present and future economic impacts of climate extremes in the United States. Glob. Environ. Change Part B: Environ. Hazards 5 (3–4), 47–50.
Changnon, S., 2003b. Measures of economic impacts of weather extremes. Bull. Am. Meteorol. Soc. 84, 1231–1235.
Chung, U., Gbegbelegbe, S., Shiferaw, B., et al., 2014. Modeling the effect of a heat wave on maize production in the USA and its implications on food security in the developing world. (submitted for publication).
Deschenes, O., Moretti, E., 2009. Extreme Weather Events, Mortality, and Migration. The Rev. Econ. Stat. 91 (4), 659–681.
Ferreira, F.H. G., Robalino, D., 2010. Social Protection in Latin America: Achievements and Limitations. World Bank.
Foreign Agricultural Service, U., 2012. Grain: World Markets and Trade. Washington DC, p. 55.
Hallegatte, S., 2007. The use of synthetic hurricane tracks in risk analysis and climate change damage assessment. J. Appl. Meteorol. Climatol. 46 (11), 1956–1966.
Hallegatte, S., Hourcade, J.-C, Dumas, P., 2007. Why economic dynamics matter in assessing climate change damages: illustration on extreme events. Ecol. Econ. 62 (2), 330–340.
Hoogenboom, G., Wilkens, P.W., Tsuji, G.Y., et al., 1999. DSSAT Version 3. University of Hawai, Honolulu, Hawaii.
Jones, J.W., Hoogenboom, G., Porter, C.H., et al., 2003. The DSSAT cropping system model. Eur. J. Agron. 18, 235–265.
Kunkel, K.E., Pielke, R.A., Changnon, S.A., 1999. Temporal fluctuations in weather and climate extremes that cause economic and human health impacts: a review. Bull. Am. Meteorol. Soc. 80 (6), 1077–1098.
Mechler, R., Hochrainer, S., Aaheim, A., et al., 2010. Modelling economic impacts and adaptation to extreme events: insights from European case studies. Mitig. Adapt. Strateg. Glob. Change 15 (7), 737–762.
Nelson, G.C., Rosegrant, M.W., Palazzo, A., et al., 2010. Food security, Farming, and Climate Change to 2050: Scenarios, Results, Policy Options. IFPRI Research Monograph. IFPRI, Washington DC p. 131.
Ortiz, R., Braun, H.-J., Crossa, J., et al., 2008. Wheat genetic resources enhancement by the International Maize and Wheat Improvement Center (CIMMYT). Genet. Resour. Crop Evol. 55 (7), 1095–1140.
Pielke, R.A., 2007. Future economic damage from tropical cyclones: sensitivities to societal and climate changes. Philos. Trans. R. Soc. A 365 (1860), 2717–2729.
Pielke, R.A., Landsea, C.W., 1998. Normalized hurricane damages in the United States: 1925–95. Weather Forecast. 13 (3), 621–631.
Piesse, J., Thirtle, C., 2009. Three bubbles and a panic: an explanatory review of recent food commodity price events. Food Policy 34 (2), 119–129.
Ray, D.K., Ramankutty, N., Mueller, N.D., et al., 2012. Recent patterns of crop yield growth and stagnation. Nat. Commun. 3, 1293.
Rosegrant, M., et al., 2012. International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT): Model Description. IFPRI, Washington DC.
Rosegrant, M.W., Ringler, C., Msangi, S., et al., 2008. International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT): Model Description. IFPRI, Washington DC.
Yano, Y., Blandford, D., Surry, Y.R., 2010. Do current US ethanol policies make sense? Policy Issues-Agricultural and Applied Economics Association, (10), 1–4.